

# Generalized fluctuation relation and effective temperatures in a driven fluid

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By numerical simulation of a Lennard-Jones like liquid driven by a velocity gradient  $\gamma$  we test the fluctuation relation (FR) below the (numerical) glass transition temperature  $T_g$ . We show that, in this region, the FR deserves to be generalized introducing a numerical factor  $X(T, \gamma) < 1$  that defines an “effective temperature”  $T_{FR} = T/X$ . On the same system we also measure the effective temperature  $T_{eff}$ , as defined from the generalized fluctuation-dissipation relation, and find a qualitative agreement between the two different nonequilibrium temperatures.

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The *Fluctuation Theorem* (FT) concerns the fluctuations of the entropy production rate  $\sigma(t)$  in the stationary nonequilibrium states of a *chaotic* driven system. We will set  $k_B = 1$  and define  $\sigma_+ \equiv \langle \sigma(t) \rangle$ , where  $\langle \cdot \rangle$  is the time average in stationary state; if  $\sigma_+ > 0$  the system is out of equilibrium. Defining the variable  $p(t) = (\tau\sigma_+)^{-1} \int_t^{t+\tau} ds \sigma(s)$  (such that  $\langle p \rangle = 1$ ), its Probability Distribution Function (PDF)  $\pi_\tau(p)$ , and the large deviations function

$$\zeta_\tau(p) = \tau^{-1} \log \pi_\tau(p), \quad \zeta(p) = \lim_{\tau \rightarrow \infty} \zeta_\tau(p), \quad (1)$$

the FT states that, for  $|p| < p^*$  (where  $p^*$  is defined by  $\lim_{p \rightarrow \pm p^*} \zeta(p) = -\infty$ ), the following relation –also called *Fluctuation Relation* (FR)– must hold:

$$\zeta(p) - \zeta(-p) = p\sigma_+. \quad (2)$$

The validity of this relation was first shown by Evans *et al* in a numerical simulation of a sheared fluid [1] and subsequently proven for *reversible* Anosov systems by Gallavotti and Cohen [2]. Gallavotti then showed that, close to equilibrium ( $\sigma_+ \rightarrow 0$ ), the FR implies the usual Fluctuation-Dissipation Relation (FDR) [3]. In the recent past, the FR has been tested under a wide class of different conditions, and is now believed to be a very general relation for chaotic systems [4, 5, 6, 7]; recently, it has been also tested in some experiments [8].

Extending the FT to the case of driven Langevin systems, Kurchan pointed out that “the FR might be violated for those (infinite) driven systems which in the absence of drive have a slow relaxational dynamics that does not lead them to equilibrium in finite times” [6]. This is (by definition) the case of driven glassy systems. Driven glassy systems have been widely studied by numerical simulations: in [9] a uniform velocity gradient  $\gamma$  was applied on a Lennard-Jones liquid (which manifests glassy behavior below the *glass transition temperature*  $T_g$  [10]) at fixed kinetic temperature  $T$ . In presence of the driving force, the system becomes stationary also below  $T_g$ , while in the absence of drive the system is not

able to equilibrate with the bath and *ages* indefinitely. It was shown that below  $T_g$  the FDR does not hold anymore (because in absence of drive the system is not able to reach equilibrium below  $T_g$ ) but can be generalized, for small driving force, introducing an “effective temperature”  $T_{eff}$  –higher than the temperature of the bath– associated with the “slow” modes that in absence of drive are responsible for the glassy behavior [9, 11]. The breakdown of the FDR and the close relation between the latter and the FR support the conjecture of Kurchan that the FR also has to be modified below  $T_g$ .

A possible generalization of the FR, of the form

$$\zeta(p) - \zeta(-p) = X p \sigma_+, \quad (3)$$

was proposed in [4] in the context of chaotic dynamical systems. It has also been proposed to define  $T_{FR} \equiv T/X$  as the “temperature” in nonequilibrium steady states [12]. A similar generalization has been proposed by many authors in the context of glassy systems, following the reported Kurchan’s observation, and some attempts have been made in order to relate  $T_{FR}$  with the effective temperature  $T_{eff}$  introduced in the generalized FDR [13, 14]. Recently, a connection between the generalized FDR and the FR has been derived in a model for the Brownian diffusion of a particle in a nonequilibrium environment [15].

However, up to now numerical studies of the FR have been performed only in the high temperature region ( $T \gg T_g$ ). The aim of this paper is to test the FR below  $T_g$  in a numerical simulation of a Lennard-Jones like liquid. We measured  $\zeta(p)$  and found that the data are consistent with Eq. 3 with  $X < 1$ , while above  $T_g$  one has  $X = 1$ , consistently with what has been found in previous works. We measured also the effective temperature  $T_{eff}$  from the generalized FDR and found a good agreement between  $T_{FR} = T/X$  and  $T_{eff}$ .

The investigated system is a 80:20 binary mixture of  $N=66$  particles of equal mass  $m$  interacting via a Soft Sphere Potential (SSP)  $V_{\alpha\beta}(r) = \epsilon_{\alpha\beta} \left(\frac{\sigma_{\alpha\beta}}{r}\right)^{12}$  ( $\alpha, \beta \in [A, B]$ ). This system has been introduced and characterized in equilibrium by De Michele *et al* [16] as a modifi-

cation of the standard LJ Kob-Andersen mixture that is known to avoid crystallization on very long time scales, and hence to be a very good model of glass former; it has been chosen because the SSP can be cut at very short distance ( $\sim 1.5\sigma_{AA}$ ) allowing the system to be very small ( $N=66$ ) in order to observe the negative values of  $p$  that are required to test Eq. 2. All the quantities are reported in units of  $m$ ,  $\epsilon_{AA}$  and  $\sigma_{AA}$ . In these units the integration step is  $dt = 0.005$ . The particles are confined in a cubic box with Lees-Edwards boundary conditions [17] at density  $\rho = 1.2$ . The shear flow is applied to the system along the  $x$  direction with a gradient velocity field along the  $y$  axis. The molecular dynamics simulation is performed using SLLOD equations of motion [17]:

$$\dot{q}_i = \frac{p_i}{m} + \gamma q_{yi} \hat{x}, \quad \dot{p}_i = F_i(q) - \gamma p_{yi} \hat{x} - \alpha p_i, \quad (4)$$

where  $F_i(q) = -\partial_{q_i} V(q)$  and  $\alpha$  is a Gaussian thermostat that fixes the kinetic energy  $\sum_i \frac{p_i^2}{2m} = \frac{3}{2}NT$ . The entropy production rate is defined as the dissipated power  $W$  divided by the kinetic temperature  $T$  [18]:  $\sigma(p, q) = W(p, q)/T = -\gamma P_{xy}(p, q)/T$ , where  $P_{xy}(p, q) = \sum_i [p_{xi}p_{yi} + q_{yi}F_{xi}(q)]$  is the  $xy$  component of the stress tensor [17].

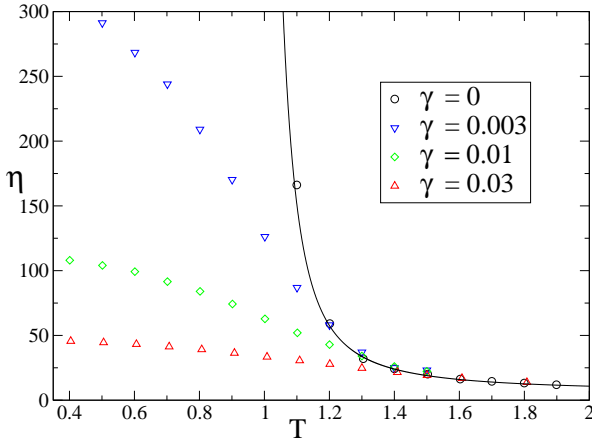


FIG. 1: Viscosity as a function of temperature for different values of  $\gamma$ . The continuous line is a fit to a Vogel-Tamman-Fulcher law,  $\eta(T) = \eta_0 \exp(\frac{AT_0}{T-T_0})$  with  $\eta_0 = 5.2$ ,  $A = 0.99$ ,  $T_0 = 0.85$ .

In Fig. 1 we report the viscosity  $\eta \equiv \langle P_{xy} \rangle / \gamma$  as a function of the temperature  $T$  for different values of the shear rate  $\gamma$ . At  $\gamma = 0$  the viscosity seems to diverge at a temperature  $T_0 \sim 0.85$ ; however, we are able to equilibrate our system only down to  $T \sim 1.1$ , that provides an estimate for the glass transition temperature  $T_g$ . For  $\gamma > 0$  the system becomes stationary and the viscosity is finite at all temperatures, even below  $T_0$ .

Very long simulation runs (up to  $2 \cdot 10^9$  time steps) have been performed to measure the PDF of the entropy

production rate along the line  $\gamma = 0.03$ . During the run,  $p(t)$  has been measured on subsequent time intervals of duration  $\tau$ . From this dataset, we constructed the histograms of  $\pi_\tau(p)$  and the large deviations function  $\zeta_\tau(p)$  defined in Eq. 1. The function  $\zeta_\tau(p)$  is observed to converge to its asymptotic value  $\zeta(p)$  for  $\tau \gtrsim \tau_\alpha$ ,  $\tau_\alpha$  being the relaxation time of the autocorrelation function of  $\sigma(t)$ .

In the upper panel of Fig. 2, we report the functions  $\zeta_\tau(p)$  for  $\gamma = 0.03$  and  $T = 1.4 > T_g$ . The asymptotic function  $\zeta(p)$  is obtained for  $\tau \gtrsim 5$  and can be described by a simple Gaussian form,  $\zeta(p) = -(p-1)^2/2\delta^2$ , even if small non-Gaussian tails are observed. In the lower panel of Fig. 2 we report  $\zeta_\tau(p) - \zeta_\tau(-p)$  as a function of  $p\sigma_+$ . The FR, Eq. 2, predicts the plot to be a straight line with slope 1 for large  $\tau$ ; this is indeed the case for  $\tau \gtrsim 5$ , consistently with what has been found in the literature [1, 5].

In the upper panel of Fig. 3, we report the functions  $\zeta_\tau(p)$  for  $\gamma = 0.03$  and  $T = 0.8 < T_g$ . In this case, the asymptotic regime is reached for  $\tau \gtrsim 6$ ; this value is not so different from the one obtained in the previous case because the change in viscosity (and hence in relaxation time) going from  $T = 1.4$  to  $T = 0.8$  is very small at this value of  $\gamma$  (see Fig. 1). Also in this case the simple Gaussian form gives a good description of the data apart from the small non-Gaussian tails. In the lower panel of Fig. 3 we report  $\zeta_\tau(p) - \zeta_\tau(-p)$  as a function of  $p\sigma_+$ . At variance to what happens for  $T > T_g$ , in this case the asymptotic slope reached for  $\tau \gtrsim 6$  is smaller than 1; thus, the FR given by Eq. 2 has to be generalized according to Eq. 3. At this temperature, we get  $X = 0.83 \pm 0.05$ .

In Fig. 4, we report the behavior of the violation factor  $X(T, \gamma = 0.03)$  (full circles) as a function of the temperature  $T$ ; note that  $X$  becomes smaller than unity exactly around  $T_g \sim 1.1$ , *i.e.* when the viscosity starts to diverge strongly (see Fig. 1). Below  $T \sim 0.4$ ,  $\sigma_+$  becomes so large that negative fluctuations of  $p$  are extremely rare and the violation factor is no longer measurable. We can conclude that below  $T_g$  the FR does not hold, and our data are consistent with Eq. 3 where the coefficient  $X$  is temperature dependent below  $T_g$  and equals 1 above  $T_g$ .

Having checked the validity of Eq. 3, following Ref. [12], we can define a nonequilibrium temperature as  $T_{FR} = T/X$ . Note that if we define  $\sigma'(t) = W/T_{FR} = X\sigma(t)$ , the variable  $p$  and the function  $\zeta(p)$  are not affected by the rescaling while  $\sigma'_+ = X\sigma_+$ . Thus, the FR for  $\sigma'$  is the usual one given by Eq. 2. If one assumes that the fluctuations of entropy production rate should satisfy Eq. 2, the entropy production rate should be given by  $\sigma'(t)$  instead of  $\sigma(t)$ .

It is interesting to compare the temperature  $T_{FR}$  with the effective temperature  $T_{eff}$  that enters the generalized Fluctuation Dissipation Relation. The latter can be measured from the relation  $T_{eff} = D/\mu$ , where  $D$  is the diffusion constant and  $\mu$  is the mobility of the particles

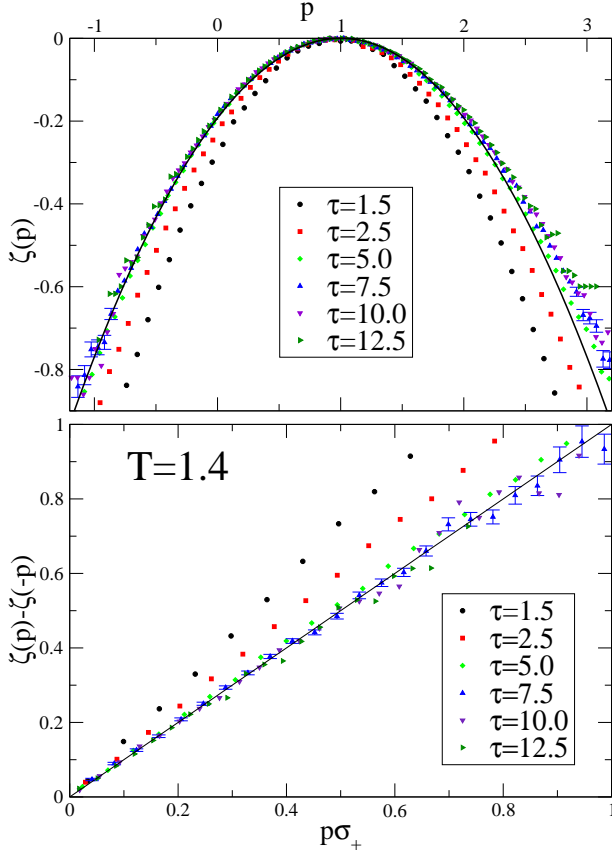


FIG. 2: Top: the large deviation function  $\zeta_\tau(p) = \tau^{-1} \log \pi_\tau(p)$  as a function of  $p$  for different values of  $\tau$  at  $T = 1.4 > T_g$  and  $\gamma = 0.03$ . Error bars are smaller than the symbols except on the tails: they are reported only for  $\tau = 7.5$  to avoid confusion. The line is a Gaussian fit to the data with  $\tau > 5$  for  $p \in [0, 2]$ . Bottom:  $\zeta_\tau(p) - \zeta_\tau(-p)$  as a function of  $p\sigma_+$ . The FR predicts the plot to be a straight line with slope 1 (full line) for large  $\tau$ .

in the considered steady state [9, 19]. This relation generalizes the usual equilibrium FDR  $D = \mu T$ ; to compute the diffusion constant and the mobility of type-A particles we followed the procedure discussed in Ref. [19]. In Fig. 4, together with  $X = T/T_{FR}$ , we report the ratio  $T/T_{eff}$  (open diamonds) as a function of the bath temperature  $T$ . The two “effective” temperatures have a similar qualitative behavior but do not coincide.

The origin of this discrepancy will be discussed in detail in [15]; roughly speaking, the point is that the modes at all frequencies contribute to the entropy production rate, while  $T_{eff}$  is the temperature of the slowest modes in the systems. At the values of  $\gamma$  we considered, the separation between a “fast” and a “slow” relaxation is not so sharp: hence,  $T_{FR}$  should be related to an average over all the frequencies of the frequency-dependent effective temperature. Note also that we are forced to use a very small system in order to observe large fluctuations

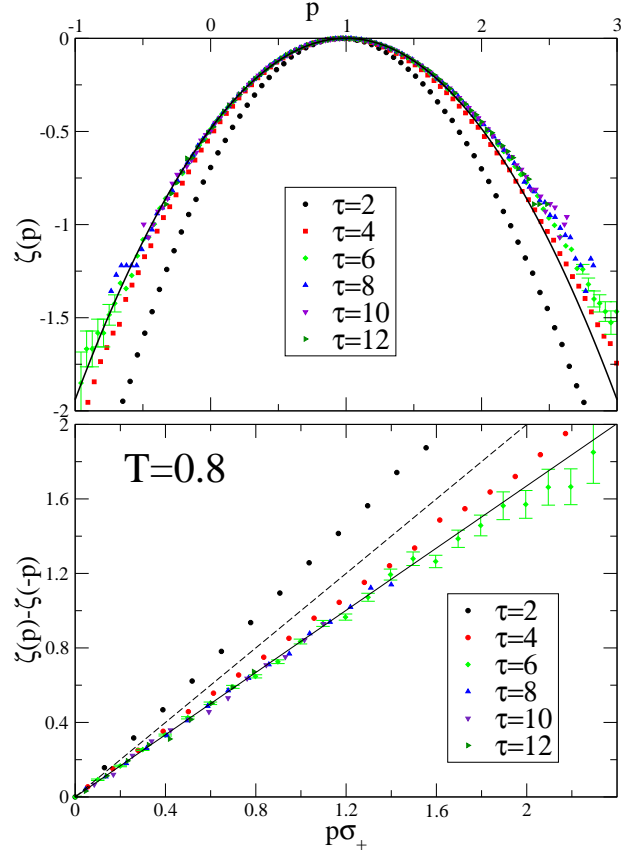


FIG. 3: Same plots as in Fig. 2 for  $\gamma = 0.03$  and  $T = 0.8 < T_g$ . In the lower panel the dashed line has slope 1 while the full line has slope  $X = 0.83$ .

of the entropy production rate, thus, size effects could affect the behavior of the investigated quantities. We believe however that the qualitative picture is correct even if size effects are not completely negligible. Future works will hopefully clarify this issue by exploring lower values of  $\gamma$  for which separation of time scales is more marked; however, for low values of  $\gamma$ , size effects are more relevant and the dynamics of the system is very slow; thus, very long simulations of bigger systems, requiring a large amount of CPU time, are mandatory.

An interesting microscopical derivation of Eq. 3 was proposed by Bonetto and Gallavotti [4], who related the factor  $X$  to the dimensionality of the attractive set of the system in its phase space. The latter can be measured by computing the Lyapunov spectrum, which in this kind of system is composed by *pairs* of conjugated exponents; the latter are constructed by pairing the largest exponent with the smallest one and so on [20]. The prediction of [4] is that  $X = \mathcal{D}/\mathcal{N}$ , where  $\mathcal{D}$  is the number of pairs where one exponent is positive and the other is negative, and  $\mathcal{N}$  is the total number of pairs. If the attractor is dense in phase space,  $\mathcal{D} = \mathcal{N}$  and  $X = 1$ . This relation is very interesting as –if true– it provides a link

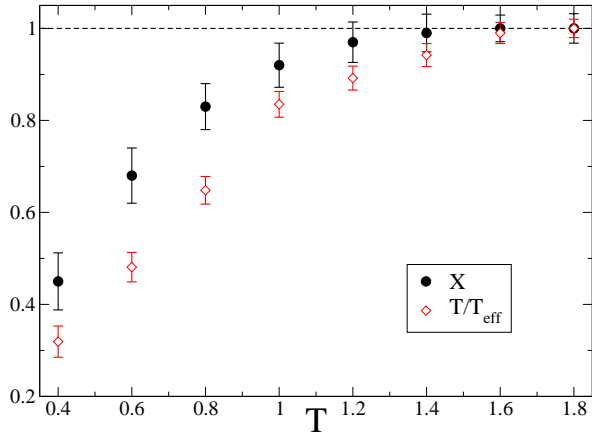


FIG. 4: The violation factor  $X = T/T_{FR}$  that enters Eq. 3 (full circles) and the ratio  $T/T_{eff}$  from the generalized FDR (open diamonds) as a function of the bath temperature  $T$  for  $\gamma = 0.03$ .

between the effective temperature and properties of the phase space of the system. The Lyapunov spectra have been measured by the mean of the standard algorithm of Benettin *et al* [21] and are reported in Fig. 5 for  $\gamma = 0.03$ ,  $T = 1.2 > T_g$  and  $T = 0.8 < T_g$ . Unfortunately, no qualitative change in the spectrum is observed on crossing  $T_g$  and in particular  $\mathcal{D}/\mathcal{N} = 1$  above and below  $T_g$ . Thus, it seems that the theory of [4] does not apply to our model below  $T_g$ . Note however that this theory is developed under the assumption of a strong chaoticity of the system, while below  $T_g$  and for  $\gamma \sim 0$  the dynamics of our system becomes slower and slower. Thus, our results should not be regarded as invalidating the conjecture of [4], but as indicating that the hypothesis of [4] (essentially, the requirement of strong chaoticity) are not satisfied by our model below  $T_g$ .

To resume, we studied the fluctuations of entropy production in a numerical simulation of a Lennard-Jones like fluid above and below the glass transition temperature  $T_g$ . We showed that below  $T_g$  the Fluctuation Relation does not hold; in particular, our data are consistent with a modified form of the FR expressed by Eq. 3. We also showed that the behavior of the temperature derived from Eq. 3,  $T_{FR} = T/X$ , is qualitatively similar to that of the effective temperature  $T_{eff}$  that is usually defined from the generalized Fluctuation Dissipation Relation. A relation between  $T_{FR}$  and  $T_{eff}$  has been proposed in [13, 14] and our result are consistent with a recent quantitative derivation of this relation in a simplified model [15]. Finally, we tested a conjecture that relates the factor  $X$  in Eq. 3 to properties of the phase space of the considered system; unfortunately, our data are not consistent with this conjecture; thus, we believe that the violation of the FR is, in our case, of different origin than that proposed in [4]. We hope that future work will

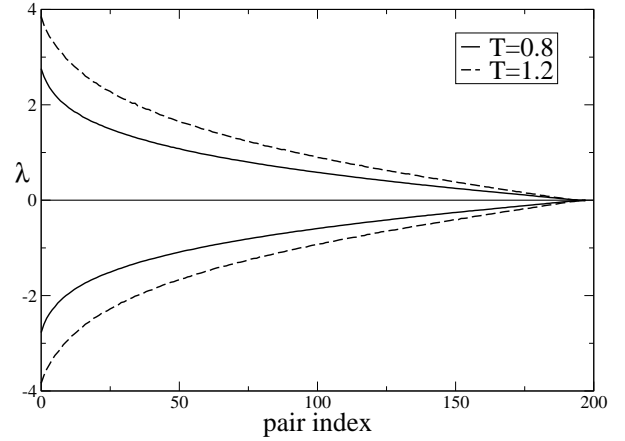


FIG. 5: Lyapunov exponents for  $\gamma = 0.03$  and  $T = 0.8, 1.2$ . For both temperatures each pair consists of one positive and one negative exponent, thus  $\mathcal{D}/\mathcal{N} = 1$ .

clarify this important issue.

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